Testing Turbulence Closure Models Against Oceanic Turbulence Measurements

J. H. Trowbridge
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
phone: 508-289-2296 fax: 508-457-2194 e-mail: jtrowbridge@whoi.edu

Grant Number: N000140110255

LONG-TERM GOALS

The long-term goals of this project are to quantify turbulence and to understand the dynamics and implications of turbulent mixing in the coastal ocean.

OBJECTIVES

The specific objectives of this project are to obtain a critical evaluation of turbulence closure models that are commonly used in the coastal ocean, and to identify ways to improve these models. Of particular interest are the MY-2.5 model (Mellor and Yamada, 1974, 1982) and the k-epsilon model (e.g., Rodi, 1987), which involve coupled equations describing turbulent kinetic energy and turbulent scale. Also of interest is the KPP model (Large et al. 1994), which determines the eddy viscosity and diffusivity in terms of boundary layer thickness and boundary fluxes of momentum and buoyancy. In the present applications, work to date has clarified the turbulence energetics (see below), so that the primary focus is on processes controlling turbulence scale, which is by far the most uncertain component of turbulence closure models.

APPROACH

The approach is to compare computations based on turbulence closure models with oceanic turbulence measurements obtained in ONR's Coastal Mixing and Optics (CMO) program and in an NSF-funded study in the Hudson estuary. Turbulence closure models produce estimates of turbulent fluxes, given the Reynolds-averaged profiles of velocity and density. In the CMO and Hudson observational studies, both turbulent fluxes and Reynolds-averaged profiles were measured. Thus the measurements permit direct tests of turbulence models, in contrast to the more common indirect tests, based on measurements of Reynolds-averaged profiles and the assumption of one-dimensional dynamics to infer turbulent fluxes. In addition to measurements of turbulent fluxes, the CMO and Hudson data sets include measurements of dissipation rates, which permits diagnosis of the turbulence energetics.

WORK COMPLETED

Work on this project has focused on two tasks. The first is comparison of computations based on turbulence closure models with measurements obtained in the CMO program. Some of this work is described by Shaw and Trowbridge (submitted). The second task is analysis of a unique set of measurements obtained from a spatial array of near-bottom velocity sensors, which were deployed in shallow water near Scripps pier, in California. Although not described in the original proposal for this

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Testing Turbulence Closure Models Against Oceanic Turbulence Measurements**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Woods Hole Oceanographic Institution,,Woods Hole,,MA, 02543**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

project, the California measurements were pursued because they explicitly determine turbulence scale, which must be inferred from temporal variability in conventional turbulence measurements. The analysis of the California measurements is described by Trowbridge and Elgar (submitted).

RESULTS

Results of the analysis of CMO measurements include successful closure of simplified balances for turbulent kinetic energy and momentum (Figure 1) and an evaluation of MO similarity theory (a simple turbulence closure model) and the KPP model (Figure 2). Detailed explanations of these results are provided in the figure captions. Of particular interest is failure of MO similarity theory (Figure 2a), in contrast to crude but quantative agreement between measurements and computations based on the KPP model (Figure 2b), because of incorporation of the effect of finite boundary layer thickness on turbulence scale.

Results of the analysis of the California measurements includes explicit determination of the scales contributing to the dynamically important alongshore component of the turbulent Reynolds shear stress (Figure 2). Of particular interest is demonstration that turbulence scales shorten during upwelling-favorable alongshore flows, probably because of the intensification of near-bottom stratification, which limits turbulence scales.

IMPACT/APPLICATIONS

This work will produce critical tests and ultimately improvements of turbulence closure models that are widely used in the coastal ocean.

TRANSITIONS

None.

RELATED PROJECTS

Trowbridge's and Y. C. Agrawal's participation in the ONR HYCODE program are capitalizing on the insights about turbulence dynamics and measurements that are being obtained as part of this study.

REFERENCES

Large, W. G., McWilliams, J. C. and Doney, S. C. 1994. Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parameterization. Rev. Geophys. Space Phys. 32, 363-403.

Mellor, G. L. and Yamada, T. 1974. A hierarchy of turbulence closure models for planetary boundary layers. J. Atmos. Sci. 31, 1791-1806.

Mellor, G. L. and Yamada, T. 1982. Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys. 20, 851-875.

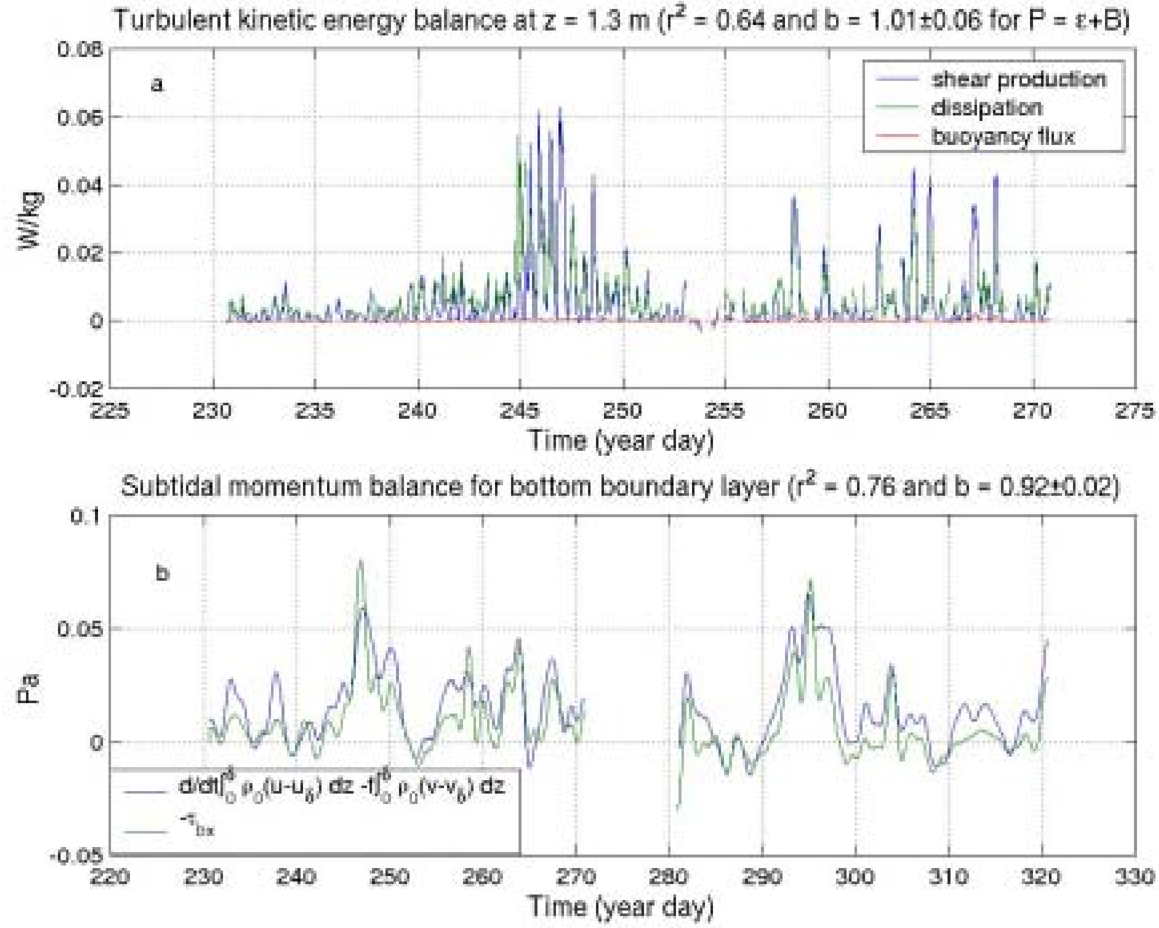

Figure 1: Tests of (a) a turbulent kinetic energy balance and (b) an alongshore momentum balance, based on measurements over the New England shelf during 1996 and 1997 as part of ONR's Coastal Mixing and Optics (CMO) program. The measurements were obtained with an array of BASS acoustic travel-time current meters (Williams et al., 1987) at heights between 0.4 and 7.0 m above bottom. The energy balance tested in (a) is shear production (P) equals dissipation ((ε) plus buoyancy flux (B). In this example, shear production and dissipation are much larger than buoyancy flux. The balance P = B + ε closes well. The momentum balance tested in (b) is integrated over the thickness of the bottom boundary layer, and involves temporal acceleration, Coriolis acceleration, pressure gradient, and bottom stress. In (b), ρ_0 is a fixed reference density, f is the Coriolis parameter, z is height above bottom, t is time, v is cross-shelf velocity, subscript δ denotes evaluation at z = δ, where δ is boundary layer thickness, and τ_{bx} is the alongshore component of the turbulent Reynolds shear stress, extrapolated to the sea floor. This calculation is based on δ = 40 m. The momentum balance closes well. In both panels, r^2 is the squared correlation coefficient and b is the regression coefficient for the left and right sides of the equation. Successful closure of the turbulent energy and momentum balances implies that the measurements of stress, dissipation, and buoyancy flux are accurate and that the turbulence energetics and bottom boundary layer dynamics are relatively simple.

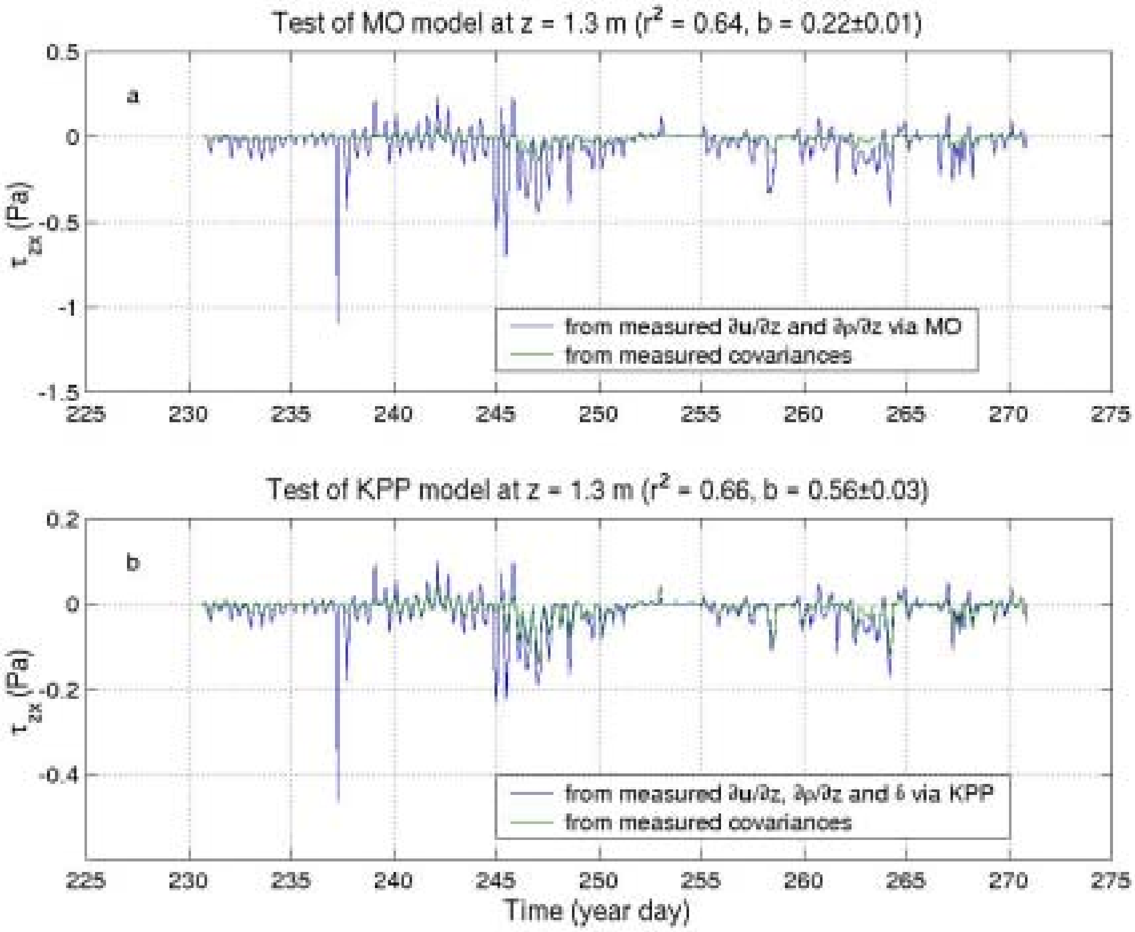

Figure 2: Tests of turbulence closure parameterizations, including (a) Monin-Obukhov (MO) similarity theory and (b) the K Profile Parameterization proposed by Large et al. (1994), based on measurements obtained during the CMO experiment. z is height above bottom, u is the Reynolds-averaged horizontal velocity vector, τ_{zx} is the alongshore component of the turbulent Reynolds shear stress, δ is boundary layer thickness, r^2 is squared correlation coefficient, and b is regression coefficient. In both panels, the Reynolds-averaged velocity and density profiles are inputs to the model, τ_{zx} is the model output, and model estimates of τ_{zx} are compared with estimates obtained directly from the turbulence measurements. In the MO model, τ_{zx} depends only on $\rho_0, z, \partial / \partial z$, and $\vartheta \partial \rho / \partial z$, where ρ is density and ϑ is gravitational acceleration. In the KPP model, τ_{zx} depends, in addition, on the thickness of the boundary layer. Both MO and KPP estimates of stress are well correlated with measured stresses. The MO estimate is smaller by a factor of five than the measurements. The KPP estimate is better because it incorporating dependence on boundary layer thickness.

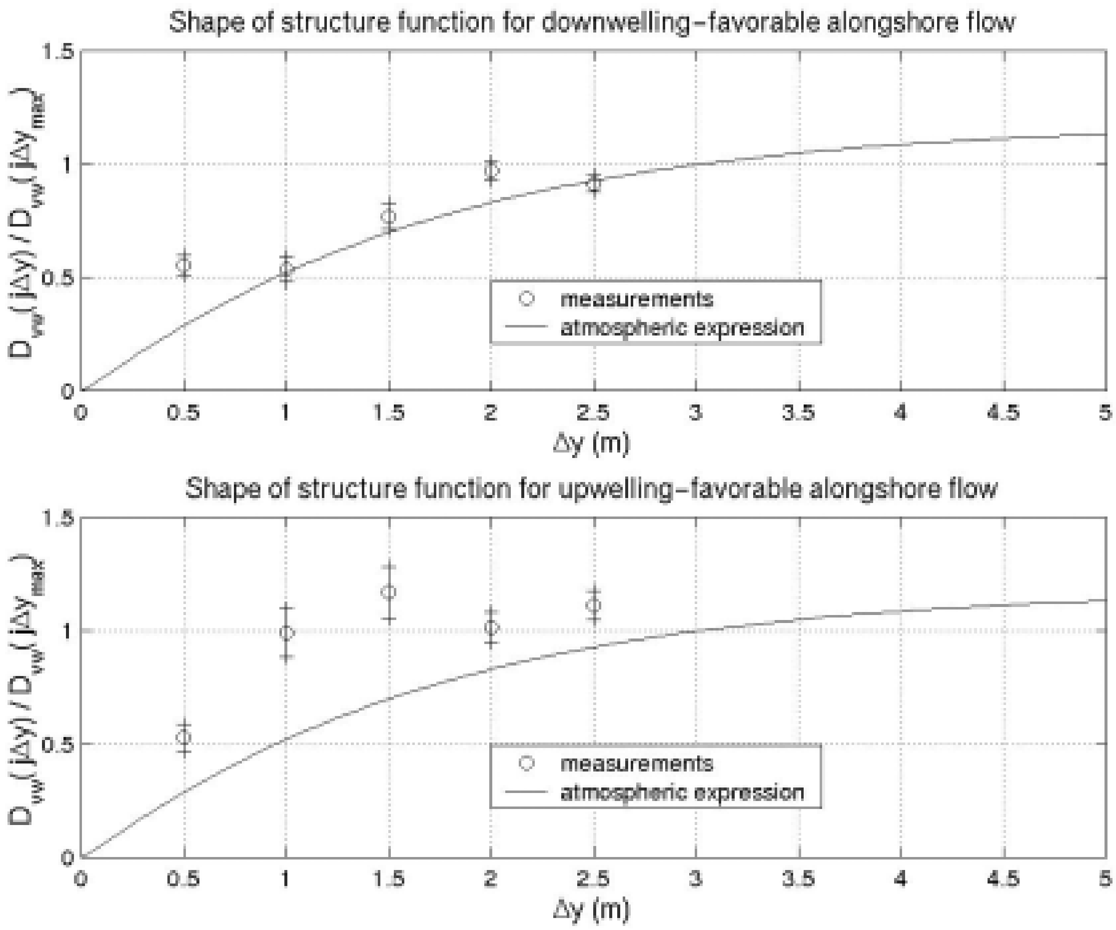

Figure 3: Estimates of the quadratic structure function $D_{\upsilon\omega}(j\Delta y)$, obtained from measurements at a water depth of approximately 4 m near Scripps pier, in California. In this application, the structure function describes the scales contributing to the alongshore component of the turbulent Reynolds shear stress. The measurements were obtained from an alongshore array of velocity sensors. Δy is alongshore separation, and $\Delta y_{\max}$ is the maximum separation resolved by the array. The measurements are compared with an expression based on measurements in the neutrally stratified atmospheric surface layer, in which the ratio of $D_{\upsilon\omega}(j\Delta y)$ to $D_{\upsilon\omega}(j\Delta y_{\max})$ depends only on $\Delta y / z$, where z is height above bottom. During downwelling-favorable alongshore flows, the measured structure function is consistent with the atmospheric expression. During upwelling-favorable alongshore flows, however, turbulence scales are shorter than indicated by the atmospheric expression, probably because of near-bottom, stable stratification, which limits turbulence scale and intensifies during upwelling. Turbulence measurements from spatial array of sensors are nearly unique in the ocean, as is the explicit demonstration that turbulence scales shorten during upwelling.

Rodi, W. 1987. Examples of calculation methods for flow and mixing in stratified flows. J. Geophys. Res. 92, 5305-5328.

Shaw, W. J., Trowbridge, J. H. and Williams, A. J. 2001. The budgets of turbulent kinetic energy and scalar variance in the continental shelf bottom boundary layer. J. Geophys. Res. 106, 9551-9564.

Shaw, W. J. and Trowbridge, J. H. 2001. The direct estimation of near-bottom turbulent fluxes in energetic wave motions. J. Atmos. Oceanic Technol. 18, 1540-1557.

Trowbridge, J. H. and Elgar, S. Spatial scales of stress-carrying nearshore turbulence. J. Phys. Oceanogr. (submitted).

Williams, A. J., Tochko, J. S., Koehler, R. L., Grant, W. D., Gross, T. F., and Dunn, C. V. R. 1987. Measurements of turbulence in the oceanic bottom boundary layer with an acoustic current meter array. J. Atmos. Oceanic Technol. 4, 312-327.

PUBLICATIONS

Trowbridge J. H., Chapman, D. C. and Candela, J. 1997. Topographic effects, straits and the bottom boundary layer, The Sea. K. Brink and A. Robinson, eds. 10, 63-68.

Voulgaris G. and Trowbridge, J. H. 1998. Evaluation of the acoustic Doppler velocimeter for turbulence measurements. J. Atmos. Oceanic Technol. 15, 272-289.

Trowbridge, J. H. 1998. On a technique for direct measurement of turbulent Reynolds stress in the presence of surface waves. J. Atmos. Oceanic Technol. 15, 290-298.

Trowbridge, J. H. and Lentz, S. J. 1998. Dynamics of the bottom boundary layer on the northern California shelf. J. Phys. Oceanogr. 28, 2075-2093.

Hill, P. S., Voulgaris, G. and Trowbridge, J. H. 2001. Controls on floc size in a continental shelf bottom boundary layer. J. Geophys. Res. 106, 9543-9550.

Lentz, S. J. and Trowbridge, J. H. 2001. A dynamical description of fall and winter mean current profiles over the northern California shelf. J. Phys. Oceanogr. 31, 914-931.

Shaw, W. J., Trowbridge, J. H. and Williams, A. J. 2001. The budgets of turbulent kinetic energy and scalar variance in the continental shelf bottom boundary layer. J. Geophys. Res. 106, 9551-9564.

Shaw, W. J. and Trowbridge, J. H. 2001. The direct estimation of near-bottom turbulent fluxes in energetic wave motions. J. Atmos. Oceanic Technol. 18, 1540-1557.

Trowbridge, J. H. and Elgar, S. J. 2001. Turbulence measurements in the surf zone. J. Phys. Oceanogr. 31, 2403-2417.

Trowbridge, J. H. and Elgar, S. J. Spatial scales of stress-carrying nearshore turbulence. J. Phys. Oceanogr. (submitted).